

Clinical characteristics influencing bioelectrical impedance analysis measurements¹⁻³

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ABSTRACT Standardization of measurement conditions is essential for obtaining accurate, precise, and reproducible bioelectrical impedance analysis (BIA) data. Errors due to lack of measurement control are propagated in subsequent calculations of body composition and contribute to differences in predictive equations among investigators. Various individual and environmental factors have been shown to influence BIA. We review the factors that have been identified from the literature as being conditions requiring standardization both for healthy subjects and for those in a medical setting. *Am J Clin Nutr* 1996;64(suppl):423S-7S.

KEY WORDS Bioelectrical impedance analysis, measurement conditions

INTRODUCTION

Several individual and environmental factors identified from the literature have been shown to influence bioelectrical impedance analysis (BIA) measurements. We review each factor and identify its potential contribution to measurement error and emphasize the need for standardization.

MEASUREMENT CONDITIONS FOR HEALTHY POPULATIONS

Accurate measurement of height and weight

On the basis of initial work by Hoffer et al (1) and subsequent studies of healthy populations (2), total body water (TBW) and fat-free mass (FFM) are most commonly estimated from linear-regression analysis through use of the equation $V = aH^2/R + bW + c$, where V is volume, H is height, R is resistance, and W is weight. For most studies, the impedance H^2/R is the single best predictor of these body compartments, accounting for 59–98% of total variability (2). More recently, multifrequency instruments have been used with the Cole-Cole model (3) and with the equations of Hanai (4) for calculation of TBW, extracellular water volume (ECW), and intracellular water volume (ICW). These more complex formulas also require measurement of length (height) and weight. Thus, inaccurate measurement of height or weight would affect estimation of body composition. When applying the cross-validated multiple-regression equation for prediction of TBW developed by Kushner et al (5), an over- or underestimation of 2.5 cm in height leads to an error of ≈ 1.0 L in TBW estimation. Similarly, an error of 1 kg in weight results in an error of 0.2 L in

predicted TBW and, more importantly, an error of 0.7 kg in body fat. Therefore, to improve BIA accuracy and precision, subjects should have vertical stature measured to the nearest 0.5 cm and weight measured to the nearest 0.1 kg; self-reports should be avoided.

Several investigators have also begun to apply a regional BIA technique for determination of muscle, fat, or fluid volumes of single body segments, eg, arm, leg, or trunk (6). For these studies, accurate measurements of segment lengths and circumferences with standard metal or cloth tape measures to the nearest 0.1 cm are necessary.

Posture and time

In the standard whole-body, tetrapolar, distal BIA technique, two current or signal electrodes are placed on the hand and foot and two voltage-sensing electrodes are applied at the wrist and ankle. Through use of this arrangement, previous studies showed that the distal arm and leg contribute approximately one-half of total body impedance (Z) because these body segments have the smallest cross-sectional surface area (7). Therefore, fluid changes localized in the distal extremities would be expected to contribute significantly to whole-body Z .

While a subject is standing, sitting, or ambulatory, gravitational forces tend to sequester ECW in the capacitance vessels and interstitium of the lower distal extremities. When subjects assume a supine position, as when BIA is performed, interstitial fluid is absorbed into the intravascular compartment and fluid shifts to the central pool (8). Thus, it can be hypothesized that temporal orthostatic changes would significantly influence BIA measurements.

Two controlled studies in our laboratory were conducted to assess the effect of body position, electrode placement, and time on multifrequency BIA. For these investigations, eight (study 1) and nine (study 2) healthy, normal-weight young adult men and women reported to the Clinical Research Center in the morning after an overnight fast. While subjects remained standing, topical self-adhesive skin electrodes were placed in the standard distal tetrapolar locations as described previously (9) and on proximal portions of the forearm and lower leg as described by Scheltinga et al (10). An impedance analyzer (Xitron 4000; Xitron Technologies Inc, San Diego) was used to

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measure a frequency sweep from 5 to 500 kHz. In the first study, BIA measurements were performed in duplicate while subjects were standing for 15 min, immediately after the subjects lay down, and again after 5 and 10 min. This duration represents the usual and customary measurement period for most BIA investigations reported in the literature. In the second study, the first measurement was obtained immediately after the subjects lay down and subsequent measurements were obtained every 10 min for the first hour, every 20 min during the second hour, and every 40 min for the remaining 2 h. Subjects remained supine in bed throughout the 4-h period (11). This duration represents conditions that may be encountered in the hospital setting.

Impedance data for five selected frequencies (5, 50, 148, 260, and 500 kHz) were chosen for analysis. Compared with measurements made while subjects were standing, distal and proximal whole-body impedance measurements were different immediately after the subjects lay down and also 5 and 10 min later (Figure 1). Changes in impedance over the entire 4-h measurement period for distal and proximal electrode placements are shown in Figure 2. As a group mean, distal tetrapolar whole-body Z increased 3% immediately with recumbance with a further 2% rise after 10 min. Repeated measurements over 4 h revealed that Z continued to rise an additional 4%. Because low-frequency Z is conducted primarily through the ECW, it is not surprising that the greatest rise in Z over the 4-h measurement period was seen at 5 kHz. Although a similar immediate rise in Z is seen with proximal electrode placement, the 4-h cumulative percentage change is about one-half of that observed with distal electrode placement.

Using a similar study design, Roos et al (12) measured the effect of changes in body posture on resistance (R) at 50 kHz in 10 healthy male subjects. BIA measurements were performed immediately after the subjects lay down; after 15, 30, 45, and 60 min of recumbance; and after subjects returned to the upright position for 5 min. A 3% mean increase in R (17 Ω) was observed after 60 min of recumbance. A decrease in R back to the initial mean value was seen after subjects resumed an upright position for 5 min. In another study of 10 subjects, Shirreffs and Maughan (13) observed a progressive increase in

whole-body Z of 13 Ω after subjects assumed a supine position for 60 min.

To further elucidate the orthostatic changes seen in Z measurements, Berg et al (14) assessed alterations in cross-sectional area and tissue fluid volume of lower limb muscles by using regional computerized tomography scans and segmental BIA of the left thigh and calf at frequencies of 1.5 and 150 kHz. Measurements were performed immediately after subjects lay down and during 120 min of supine bed rest. Calf and thigh muscle cross-sectional area decreased by means of 5.5% and 1.9%, respectively, reflecting caudal shifts of water. Fluid loss, as measured with BIA and by assessing change in radiologic density of muscle tissue, averaged 10.9% in calf and 2.5% in thigh after 2 h. Thus, postural changes in BIA appear to result from lower-extremity fluid shifts, which alter limb volume and cross-sectional area and induce changes in muscle hydration.

These studies showed that the transition from a standing to supine position is characterized by three orthostatic BIA time curves: an immediate 1–2 min rapid component (erect to supine), a less rapid intermediate stage lasting 40–80 min, and a slow phase that continues for an additional 3 h. The most significant postural change in Z occurs over the first hour. Overall, observed increases in Z are greatest for lower frequencies (≤ 10 kHz), reflecting ECW shifts. Inappropriate application of predictive equations from the literature, which commonly measure Z or R within 5 min after subjects lie down, to individuals who are restricted to bed rest for several hours or days may lead to errors of ≈ 1.0 – 1.5 L in predicted TBW. Greater errors will likely result in predicting ECW because this compartment is more dependent on gravitational shifts. Thus, standardization of conditions must include the length of time the subject is recumbent before the measurement is performed.

Abduction of limbs

In whole-body BIA, body segments are assumed to be connected in series (ie, arm to trunk to leg). Due to their geometrical shape, the extremities contribute $\approx 90\%$ of whole-body Z . Furthermore, most of the extremity Z is accounted for by the distal segments of the upper and lower limbs as a result of their lower cross-sectional area (15). Published BIA prediction

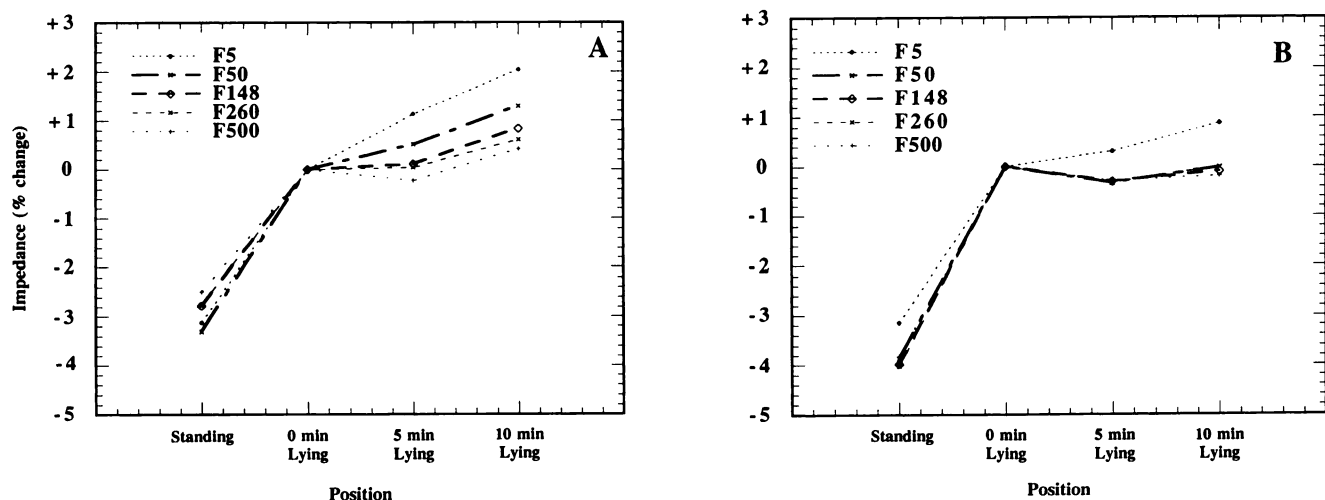


FIGURE 1. Effect of posture and time on percentage change of distal (A) and proximal (B) tetrapolar whole-body impedance for five selected frequencies (5, 50, 148, 260, and 500 kHz). Data are shown for change in impedance from standing to lying over the first 10 min.

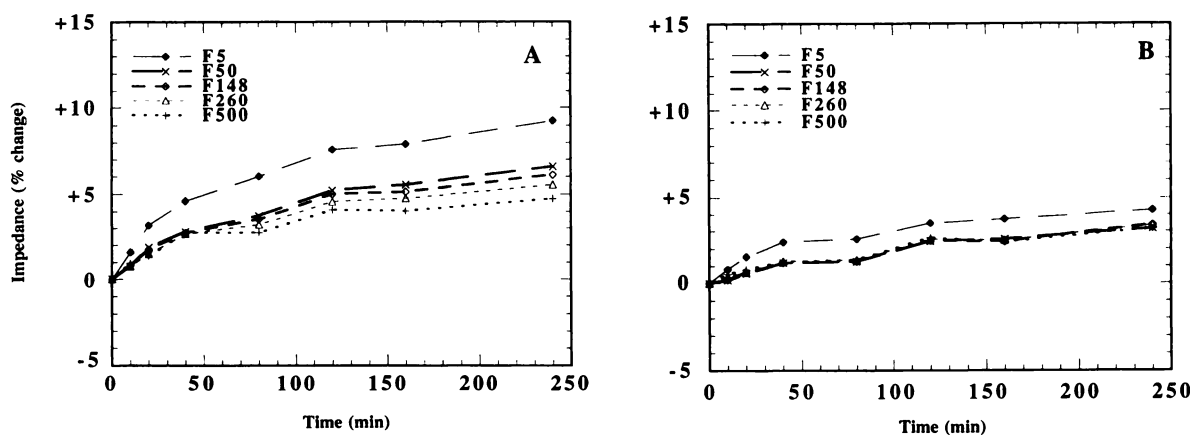


FIGURE 2. Effect of posture and time on percentage change of distal (A) and proximal (B) tetrapolar whole-body impedance for five selected frequencies (5, 50, 148, 260, and 500 kHz). Data are shown for change in impedance from immediately lying down (time 0) to 4 h. Reproduced from *Age & Nutrition*, with permission from the publisher (10).

equations are based on this electrical series paradigm. Thus, adduction or crossing of limbs would “short circuit” the electrical path, giving rise to spurious low Z values. These errors can range from 18% for contact of crossed legs to 43% for contact of the hands to the waist, both of which are errors that occur with skin-to-skin contact conditions.

Consumption of food or beverage

Consumption of food or fluids before BIA measurements are made could influence Z by changing TBW and ECW volumes. However, depending on the timing of the measurement and the amount of food or fluid ingested, one could hypothesize that a meal could have little or no effect on the prediction of TBW. Immediately after intake and for several hours thereafter, the constituents of the meal, as well as the gastric, biliary, pancreatic, and intestinal secretions stimulated by the meal, are contained within the gastrointestinal tract. Localization of up to 2 L of fluid within the abdominal cavity has previously been shown to be “electrically silent” (16–18). This segmental underrepresentation is due to the large cross-sectional surface area of the trunk, which contributes < 10% of whole-body Z . Measurements obtained several hours postprandially, after absorption of fluid into the bloodstream, can influence Z depending on the volume change. However, if one assumes that an average TBW is ≈ 45 L in young adult men (60% of body weight) and 32 L in young adult women (50% of body weight) (19), postprandial absorption of 1 L would be expected to increase TBW by 2% and 3% in young adult men and women, respectively.

Several investigators have compared R or Z measurements before and after ingestion of beverages or a meal. In a study of 12 healthy men, Fogelholm et al (20) measured changes in R at 50 kHz after an overnight fast, 1 h postmeal, and again every 1.5 h for 7 h. Beginning 1 h after a low- or high-electrolyte 2400-kJ meal, R increased initially $\approx 0.6\%$, followed by an average reduction of 0.8% that lasted several hours. However, the authors noted that individual responses were more unpredictable; the largest change measured was 4%. Deurenberg et al (21) evaluated the effect of a liquid-formula meal (1950 kJ) or different drinks [200 mL; normal tea or beef tea (bouillon)] on BIA at 50 kHz. Mean whole-body Z decreased ≈ 13 –17 Ω

by 2–4 h after the meal, representing a 3.3% change in Z . Ingestion of beef tea resulted in a 0.8% decrease in Z at 20 min. Finally, Elsen et al (22) assessed the immediate effect of ingestion of 750 or 1000 mL oral rehydration solution or pure water in 10 subjects. No significant changes in R were seen after consumption of either fluid.

Recent ingestion of a meal or beverage appears to have a minimal effect on whole-body Z during the first hour. Weight, however, will be increased and thus body fat may be overestimated. Depending on the experimental condition, Z may decrease from 4 to 15 Ω over a 2–4-h period after a meal, generally representing a change of < 3% in Z . These changes can be controlled by obtaining BIA measurements ≥ 8 h postprandially.

Recent exercise

Exercise can effect BIA measurements by at least three hypothesized mechanisms. 1) The hemodynamic response to exercise consists of increased cardiac output and blood flow to skeletal muscles. Increased vascular perfusion and warming of muscle tissue will reduce Z and muscle resistivity (ρ). 2) The process of heat dissipation includes increased cutaneous blood flow and vasodilation, increased skin temperature, and sweating. These changes should also reduce Z . 3) Sensible and insensible fluid losses result in dehydration, loss of TBW, and an increase in Z . Thus, BIA measurements should vary depending on the muscle groups involved and the intensity of exercise, changes in skin blood flow and heat production, and amount of fluid loss.

In their study of 30 healthy young men, Liang and Norris (23) examined the effects of 30 min of moderately intense exercise on a treadmill on R and reactance (X_c) measured at 50 kHz. Tetrapolar BIA was performed before exercise, repeated immediately after exercise, and again after 1 h recovery from exercise. Additionally, skin temperature (measured with an infrared temperature scanner) and skin blood flow and velocity (measured with a laser Doppler flow meter) were determined at each of the three time points. Subjects were allowed to drink water ad libitum after exercise, thus avoiding significant changes in hydration status. Compared with baseline, exercise was shown to decrease $R \approx 3\%$ and X_c by 8% immediately

postexercise; measurements returned to normal when repeated 1 h later. The changes in R and X_c coincided with a 1.4-fold increase in skin blood volume, a 2-fold increase in skin blood velocity, and a 3-fold increase in skin blood flow. Cutaneous temperature increased from a mean of 31.1 °C to 32.4 °C. Using a different approach, Lukaski et al (24) performed BIA measurements in 104 female and male varsity athletes under two experimental conditions: a controlled state (no preceding exercise and ≥ 2 h after a light meal) and an uncontrolled state (without regard to immediately preceding exercise, level of hydration, or absorptive state). Although there was a clinically insignificant average change in R and X_c of $< 1\%$, the SE in predicting FFM was reduced by 0.8 kg (2.04 compared with 2.85) when controlled conditions were observed. Even though the changes in BIA were modest, these studies show that measurements of R and X_c are influenced by recent exercise. Thus, to reduce measurement errors in the method, BIA should not be performed within several hours of moderate to strenuous exercise, and hydration status should be completely corrected.

Reproducibility of BIA measurements

Reliability or reproducibility of repeated measurements is dependent on instrument accuracy and precision and biological variations. Analytic errors are addressed in another paper in this supplement (25). As noted, biological day-to-day variation is due to many factors, including differences in normal hydration, food intake, activity level, and duration of recumbance. Although several studies have determined the CV of repeated BIA measurements at 50 kHz, standard conditions were not always used. Nevertheless, when triplicate R measurements are performed in a subject over several minutes, minimal variations of 1–5 Ω are usually seen. Reported mean CVs for within-day R measurements are ≈ 1 –2%; daily or weekly intraindividual variability is slightly larger, ranging from $\approx 2\%$ to 3.5% (9, 26–28). Day-to-day CV increases for frequencies < 50 kHz (29). Overall, the within-subject Z variability is higher in women, which appears to be due to changes in hydration status related to the menstrual cycle (30). One author suggests that several BIA measurements be taken during the cycle and averaged rather than a single determination so as to better estimate body composition (31).

MEASUREMENT VARIABLES IN THE MEDICAL SETTING

To date, few studies of disease-associated alterations in BIA measurements have been systematically addressed. However, from a theoretical point of view, it is clear that the use of BIA in the medical setting requires attention to multiple variables that may influence the underlying principles of the technique. Significant changes in hydration status, disturbances in fluid distribution, and differences in the ratio of ECW to ICW will alter Z measurements. Although changes in TBW can be assessed directly through use of BIA, the assumptions used in estimating FFM and fat mass will be affected. Furthermore, alterations in serum electrolytes, hematocrit, and blood flow will result in changes in Z and ρ independent of fluid volume. Other unique considerations include patients with cutaneous diseases that may modify electrode-skin electrical transmission, patients with amputations and those with regional alter-

ations in skeletal muscle tissue (poliomyelitis and muscular dystrophies). Additionally, fluid distribution and vascular perfusion will have significant effects on the application of BIA in the clinical population.

Changes in fluid distribution


The distal tetrapolar method presupposes that the body composition of the arm and leg is reflective of whole-body changes because these segments contribute $\approx 90\%$ to total Z . Thus, any variable that causes localized changes in the arm or leg may lead to inaccurate FFM and TBW determinations. The most significant confounding variable is edema of the distal extremities. This is commonly caused by peripheral venous insufficiency, late stages of pregnancy, some medications, and other more serious medical problems such as congestive heart failure, cirrhosis, nephrotic syndrome, hypoalbuminemia, and lymphedema. Alternatively, localized fluid accumulation in the abdomen or thorax, due to ascites, peritoneal dialysis, or pleural effusion, will be underestimated because the trunk contributes $< 10\%$ to whole-body Z .

Changes in vascular perfusion

Bedside application of BIA in the intensive care unit has been considered as a method for monitoring fluid status and changes in the ratio of ECW to ICW (32–35). Redistribution of systemic blood flow, however, is also commonly seen in this setting. Reduction in cutaneous blood flow (due to cardiac failure, shock, or postoperative hypothermia) and increased skin blood flow (due to hyperthermia) are often encountered. Caton et al (36) evaluated the effect of cutaneous changes in skin temperature on BIA at 50 kHz in eight adult men. Subjects were warmed and cooled in an environmental chamber by changes in ambient air conditions: mean skin temperature at the hand and foot was raised and lowered to 33.4 °C and 24.1 °C, respectively. Although baseline R was not mentioned, average R was significantly and consistently greater in the cool condition compared with the warm (461 Ω compared with 426 Ω), an 8% potential error.

To further explore these factors, our group conducted controlled experiments with six normal, healthy, young adult subjects in the Clinical Research Center (37). After the subjects had lain 2 h in a supine position in a thermoneutral environment to minimize orthostatic changes, heating-cooling blankets were used to raise and lower skin temperature to 36.8 °C and 26.9 °C, respectively, from a baseline temperature of 29.3 °C. Impedance was measured with a multifrequency analyzer and distal tetrapolar placement of electrodes. With heating, Z decreased at all frequencies by ≈ 50 –55 Ω (8%). Conversely, cooling was associated with an increase in Z of 5–31 Ω , the greatest change occurring at 5 kHz (4%). Although these alterations in Z are independent of actual whole-body volume changes, calculations of TBW will vary by > 2 L as a result of the localized effect of heating and cooling. Skin temperatures ranging from 27 °C to 39 °C may also be encountered in field studies depending on environmental conditions of ambient air temperature and humidity (38). Thus, changes in cutaneous and muscle blood flow will have profound effects on BIA measurements in both the hospital and field settings.

CONCLUSION

BIA has been shown to have an uncertainty of 2–4% for the prediction of TBW and FFM in healthy subjects. To achieve or improve this precision, however, users must accurately measure the subjects' heights and weights, and standardize conditions with respect to body position, previous exercise, dietary intake, and skin temperature. Although minor violations of some of these measurement conditions can be clinically tolerated, significant errors in predicting body composition will result when these conditions are collectively ignored. Use of BIA in the medical setting is likely to produce the greatest errors. Therefore, data obtained in the hospital need to be interpreted with caution. 

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